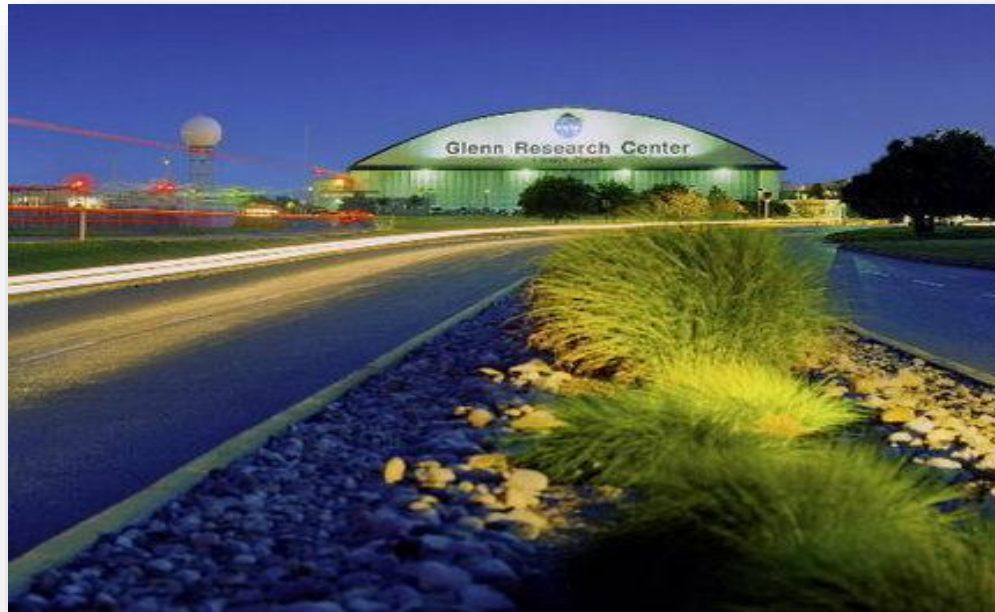


# A Decade of SMA Activities at NASA-GRC, Material Challenges, and Future Prospects



**Othmane Benafan– NASA Glenn**  
High Temperature & Smart Alloys Branch  
Materials and Structures Division

***HIGH TEMPERATURE SHAPE MEMORY ALLOY RESEARCH and TECHNOLOGY  
(HT-SMART)***

Mar. 24, 2015

# It Takes a Team...



- ☐ Neutron/synchrotron diffraction
- ☐ HTSMAs characterization

- ☐ Constitutive modeling

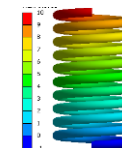
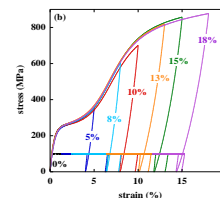
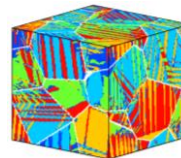
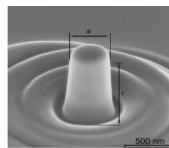
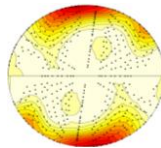
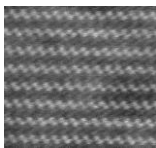
- ☐ Superelastic/bearing alloys
- ☐ Lattice deformation theory

- ☐ Alloy development
- ☐ Mechanical Characterization

- ☐ Single crystals
- ☐ SMA machining

- ☐ HTSMA Microstructure
- ☐ Modeling

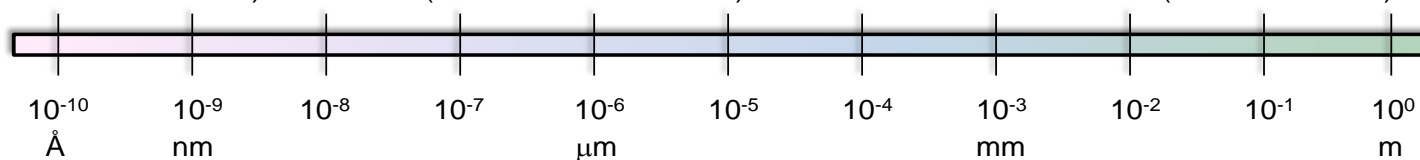
- ☐ Atom probes
- ☐ Microstructure



**ATOMIC SCALE**  
(NANOMATERIALS)

**MICRO-SCALE**  
(MICROSTRUCTURES)

**STRUCTURAL SCALE**  
(COMPONENTS)





# NASA SMA Team

- **Ron Noebe**
- **Santo Padula II**
- **Glen Bigelow**
- **Anita Garg**
- **Darrell Gaydosh**
- **Timothy Halsmer**
- **Othmane Benafan**
- **(Branch Chief: Joyce Dever)**



# Our Goals – Materials, **Infrastructure**, **Applications**

- **Materials:**

- Develop new shape memory alloys ranging from cryogenic to high temperature for use in adaptive structures, and lightweight, solid-state actuation systems .
- Adjust material properties through alloying, processing, and thermo mechanical understanding.
- Identify methods to establish good stability, durability, workability, and work output amongst others

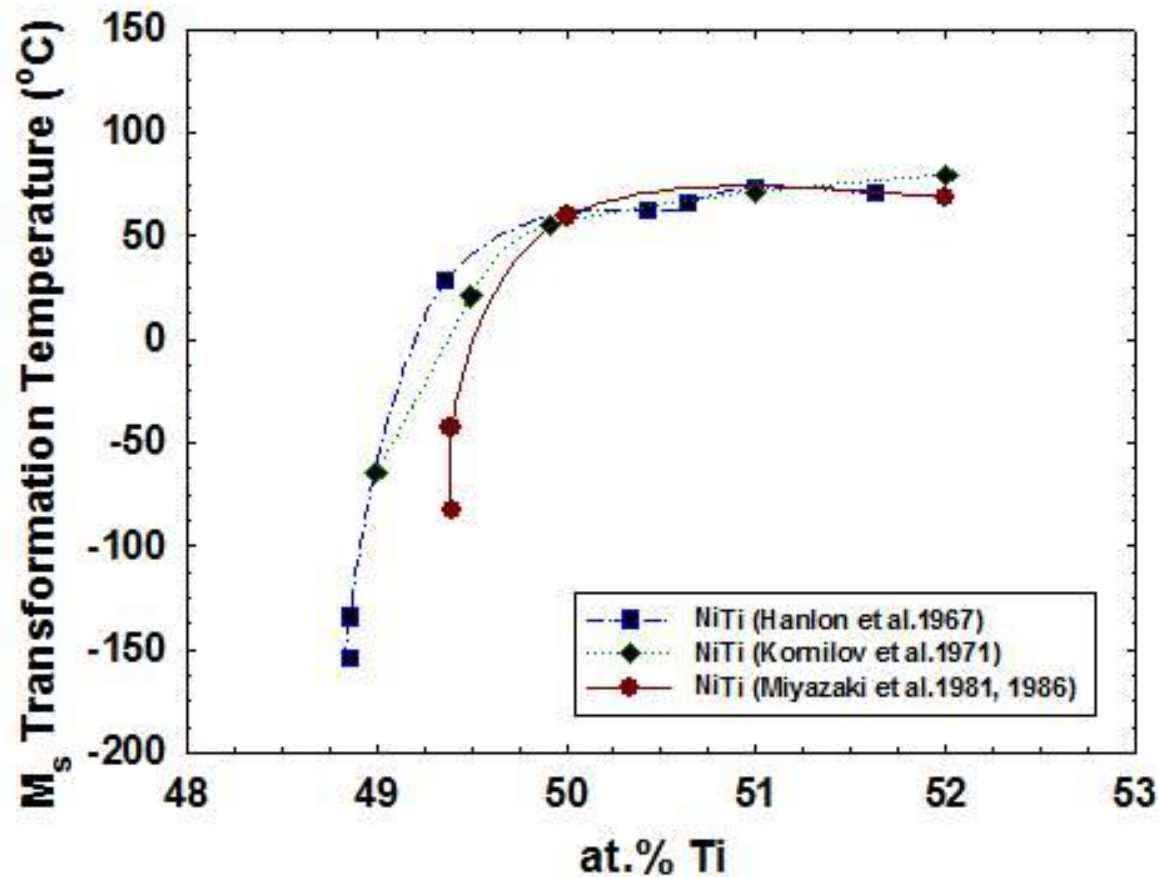
- **Infrastructure:**

- Develop laboratory testing capability and methods to evaluate and characterize SMA properties/ performance.
- Generate material(s) data sheets and databases
- Determine test standards/methodologies
- Component or subcomponent testing/modeling

- **Applications:**

- Identify/build applications to benefit the aeronautics and space design challenges
- Design methodologies
- Commercialization

# Development of Shape Memory Alloys: Challenges and Lessons Learned



# Development of Shape Memory Alloys: Challenges and Lessons Learned

## High transformation temperatures

- Above 100 °C
- Good work output
- Thermal stability

## Durability

- Loading history
- Functional fatigue
- Structural fatigue

## Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

## Workability/Processing

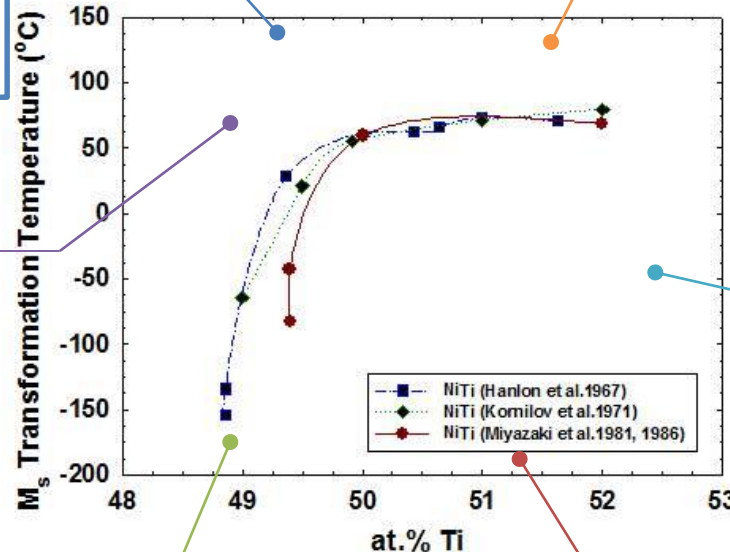
- Ductility
- Composition control
- Heat treatment

## Dimensional stability

- Cyclic stability
- Stress-strain relationship

## Certification

- Testing standards
- Material certification
- Database





# 55 Years after Nitinol Discovery

## Metals

NiTi, NiTiFe, NiTiNb, NiTiCu, NiTiPd,  
NiFeGa, NiTiCo CuZn, CuZnAl, CuAlNi,  
CuAlNiMn, CuSn FePt, FeMnSi, FeNiC

AgCd  
AuCd  
CoNiAl

NiTiHf, NiTiZr, TiNiPd, TiNiPt,  
ZrRh, ZrCu, ZrCu NiCo,  
ZrCuNi CoTi, TiMo, TiNb,  
TiTa, TiAu, UNb, TaRu, NbRu,  
FeMnSi

## Magnetic/Ferromagnetic

NiMnGa, FePd, NiMnAl,

FePt, Dy, Tb, LaSrCuO,  
ReCu, NiMnIn, CoNiGa

## Ceramics

ZrO<sub>2</sub> (PSZ), MgO,  
CeO<sub>2</sub>, PLZT, PNZST

PTFE, PU, Poly-caprolactone, EVA + nitrile  
rubber, PE, Poly-cyclooctene, PCO– CPE blend

PCL–BA copolymer, Poly(ODVE)-co-BA,  
EVA + CSM, PMMA,  
Copolyesters, PET-PEG

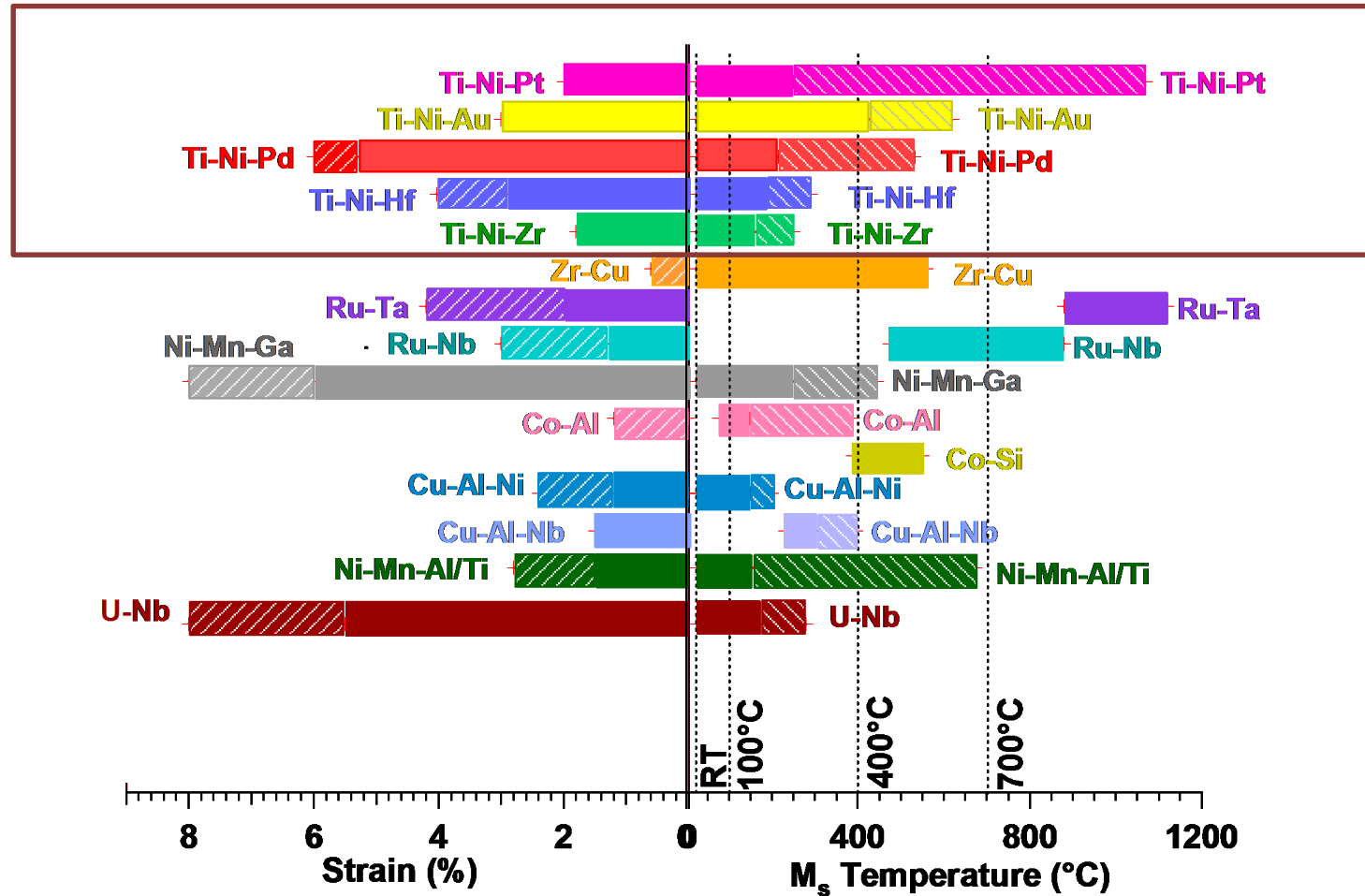
## Polymers

## Others

Thin films, hybrids...

# Development of Shape Memory Alloys:

## High Temperature Shape Memory Alloys (HTSMAs)



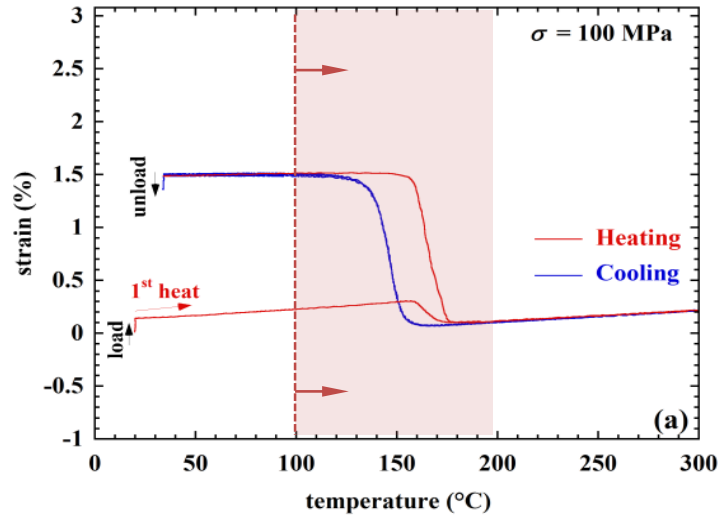
Ma et al. (2010)



# Development of Shape Memory Alloys:

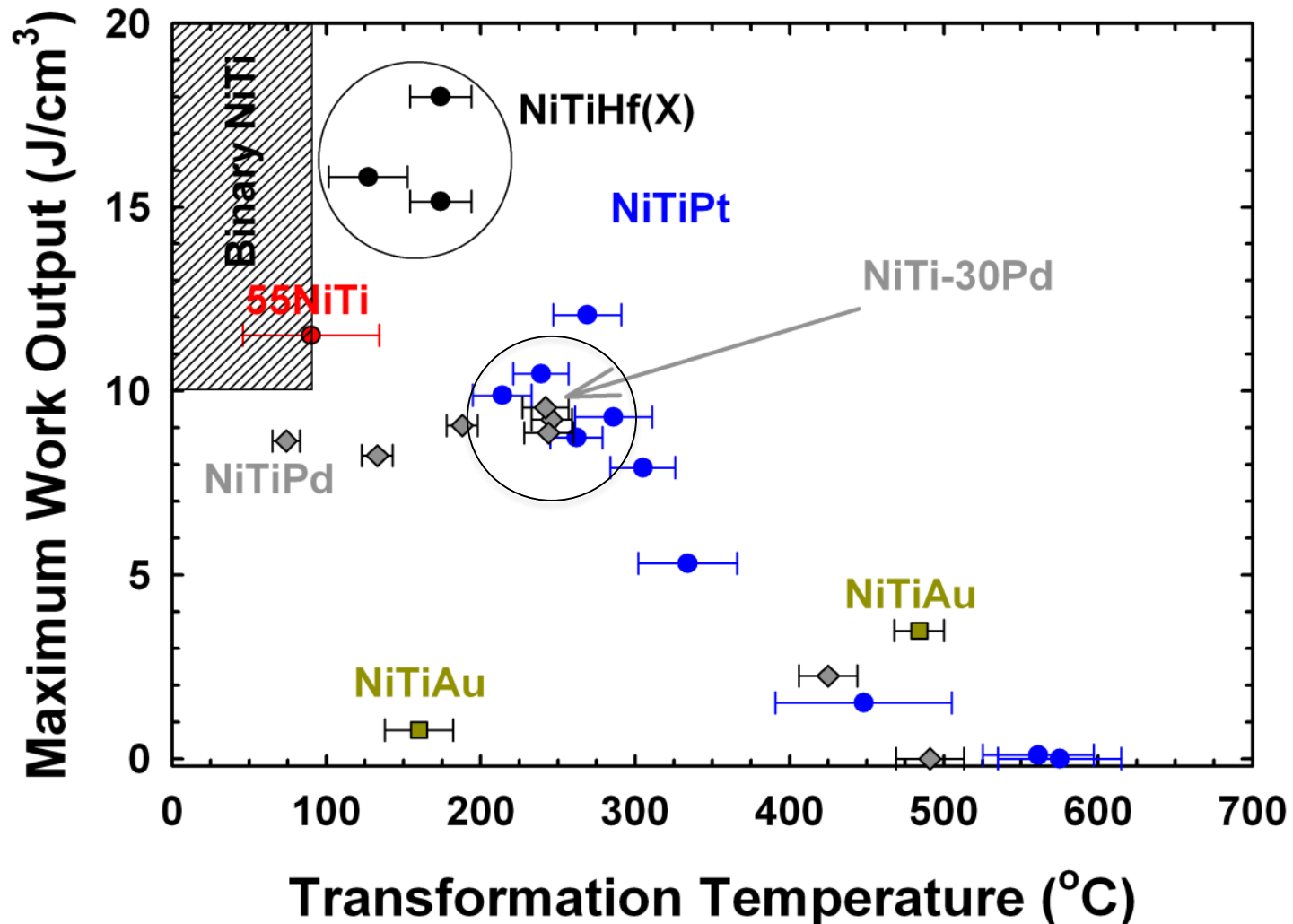
## NiTi –Based HTSMAs

NiTiHf

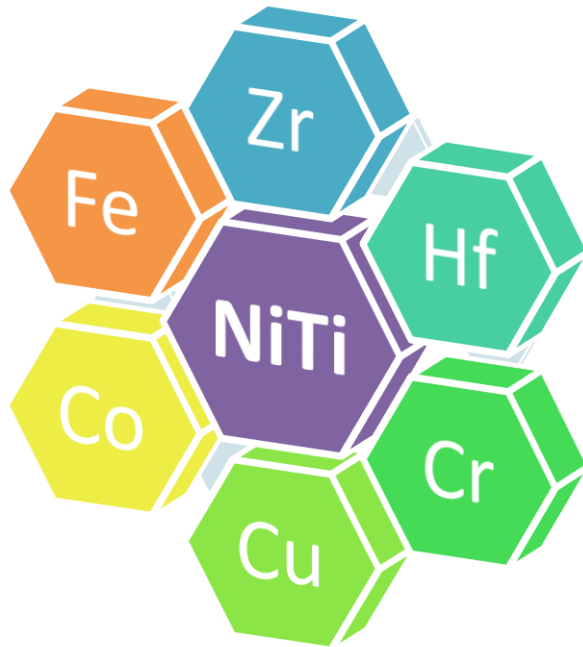
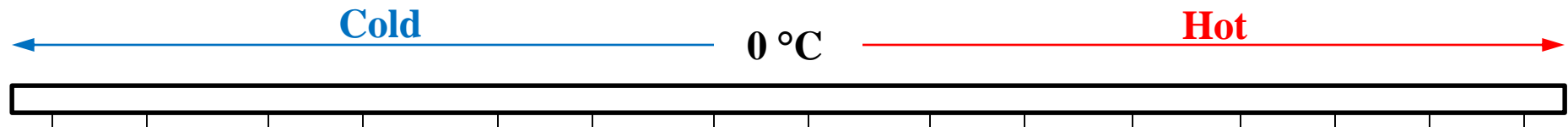


# Development of Shape Memory Alloys:

## HTSMAs Summary



# Materials – High and Low Temperature SMA



## Low Temperature SMAs

**NiTi**  
**NiTiFe**  
**NiTiCo/Cr**  
**NiTiCu**  
**NiTiHf/Zr**



## High Temperature SMAs

**NiTiHf**  
**NiTiZr**  
**NiTiPd**  
**NiTiPt**  
**NiTiAu**

# Development of Shape Memory Alloys: Challenges and Lessons Learned

## High transformation temperatures

- Above 100 °C
- Good work output
- Thermal stability

## Durability

- Loading history
- Functional fatigue
- Structural fatigue

## Modeling

- Micromechanics
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## Workability/Processing

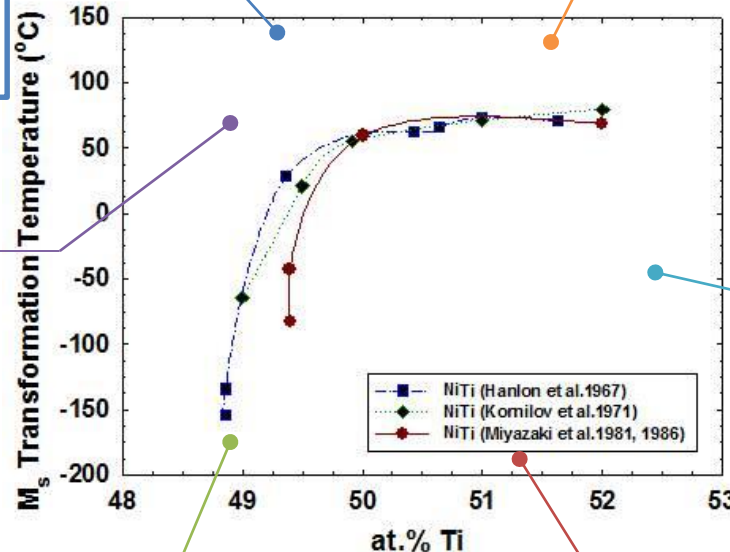
- Ductility
- Composition control
- Heat treatment

## Dimensional stability

- Cyclic stability
- Stress-strain relationship

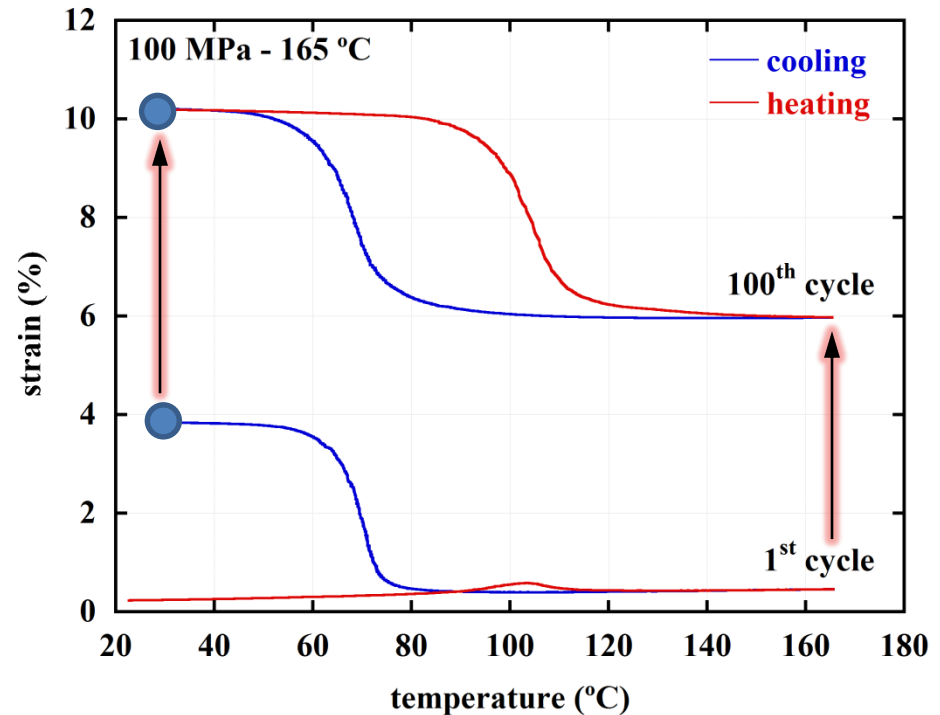
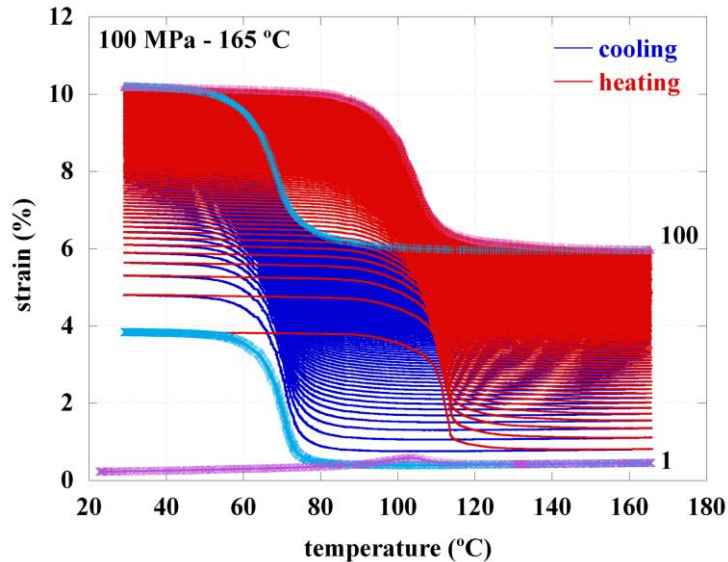
## Certification

- Testing standards
- Material certification
- Database



# Development of Shape Memory Alloys:

## How about Dimensional Stability?



## How to make the material/actuator stable?

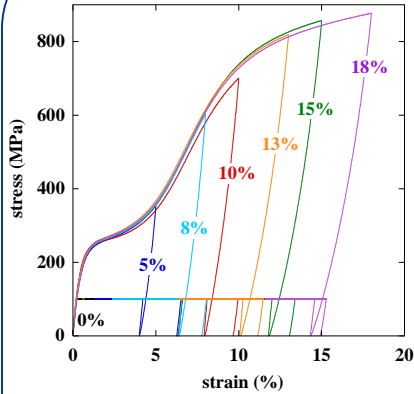
- Solution 1: Thermomechanical “training” (e.g., cycling, reverse loading...)
- **Solution 2: Alloying and microstructural control (e.g., precipitation hardening, grain refinement)**



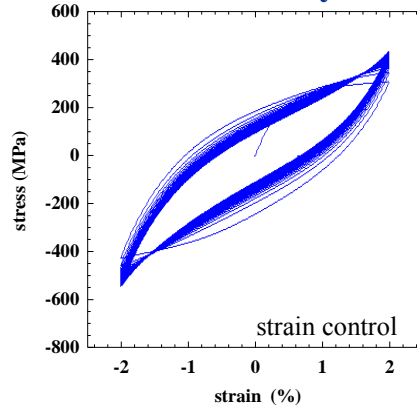
# Thermomechanical Testing

## Uniaxial (tension/compression)

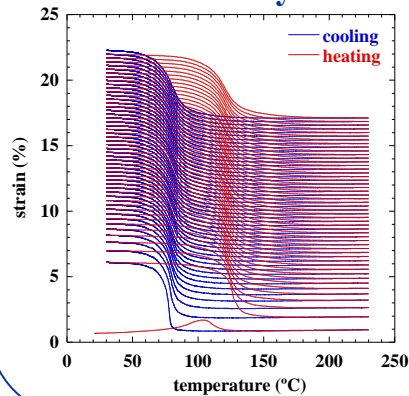
### Isothermal monotonic



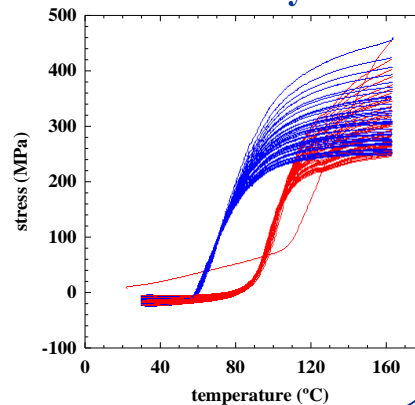
### Isothermal cyclic



### Isobaric cyclic



### Isostrain cyclic

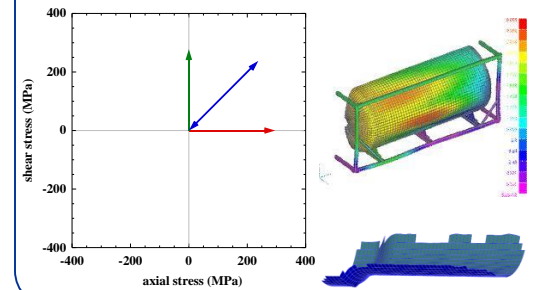


## Geometries

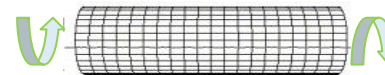
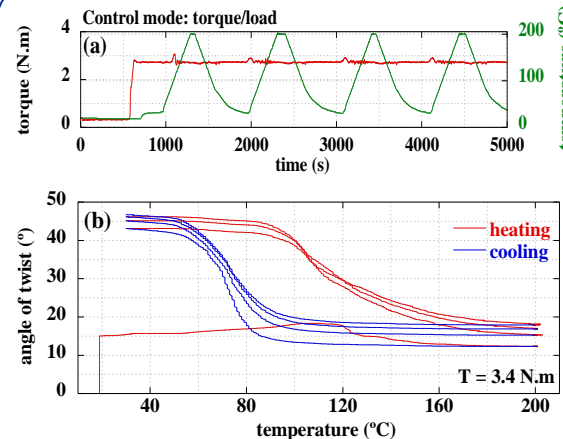


## Multiaxial

- Proportional/non-proportional loading
- 3D strain measurement
- Torque/force/twist/displacement control capability



## Torsion



## Hot grip testing

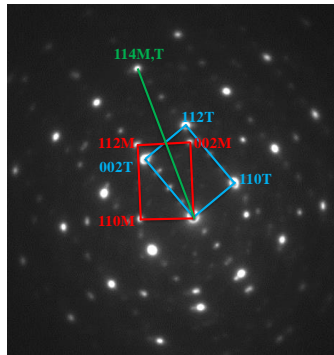
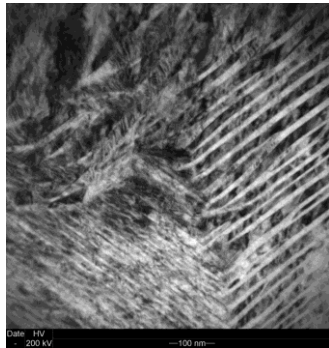




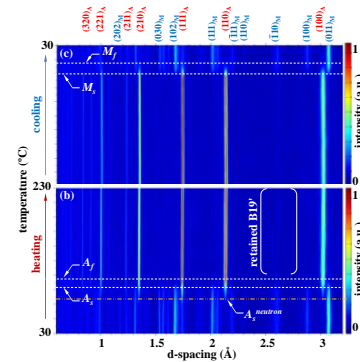


# Microstructural Control towards Stability

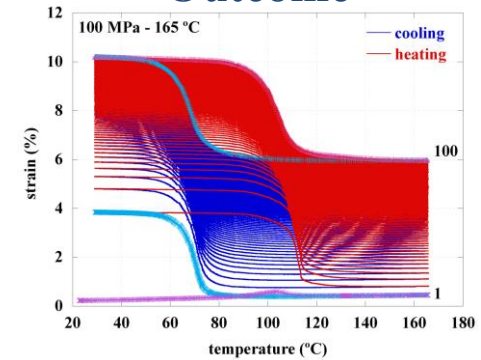
## Electron diffraction



## In situ diffraction



## Outcome





# Development of Shape Memory Alloys: Challenges and Lessons Learned

## High transformation temperatures

- Above 100 °C
- Good work output
- Thermal stability

## Durability

- Loading history
- Functional fatigue
- Structural fatigue

## Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

## Workability/Processing

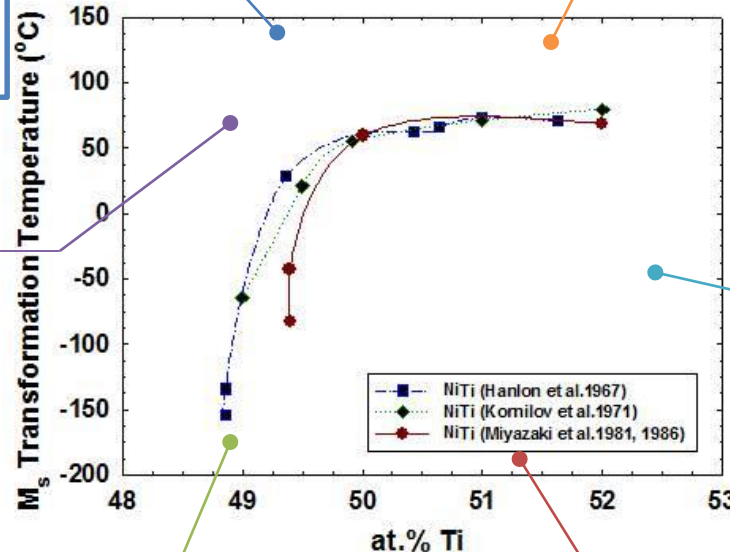
- Ductility
- Composition control
- Heat treatment

## Dimensional stability

- Cyclic stability
- Stress-strain relationship

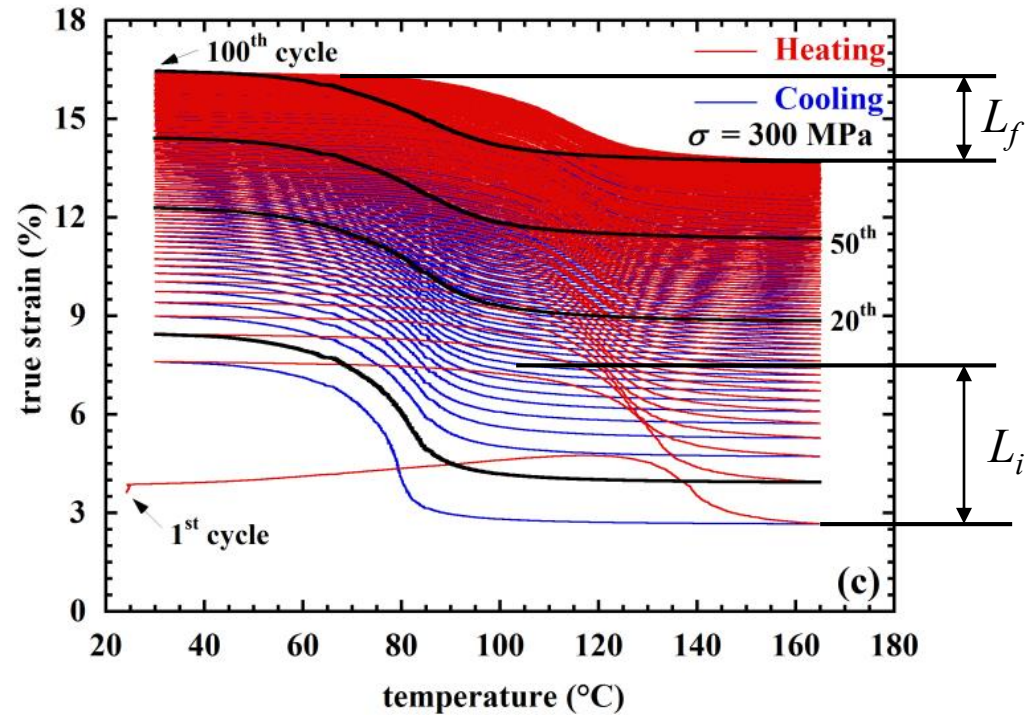
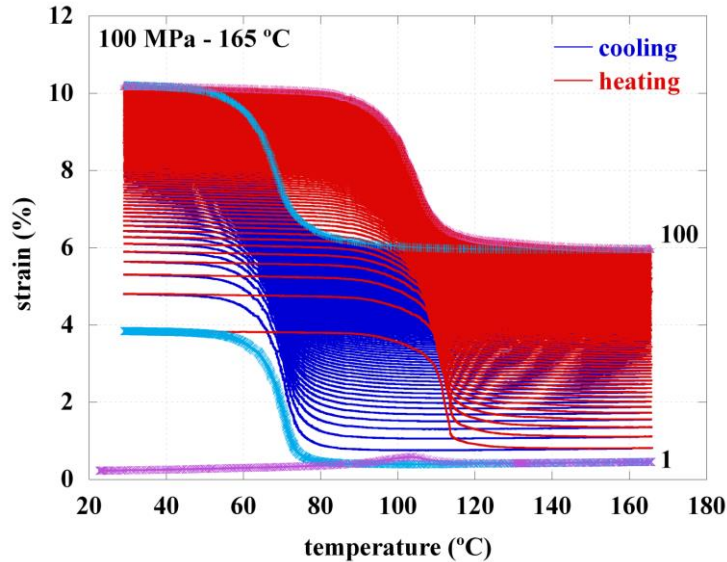
## Certification

- Testing standards
- Material certification
- Database



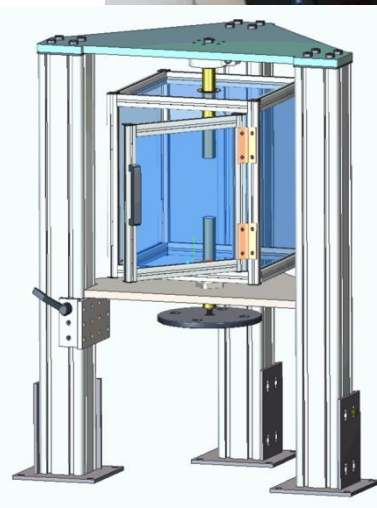
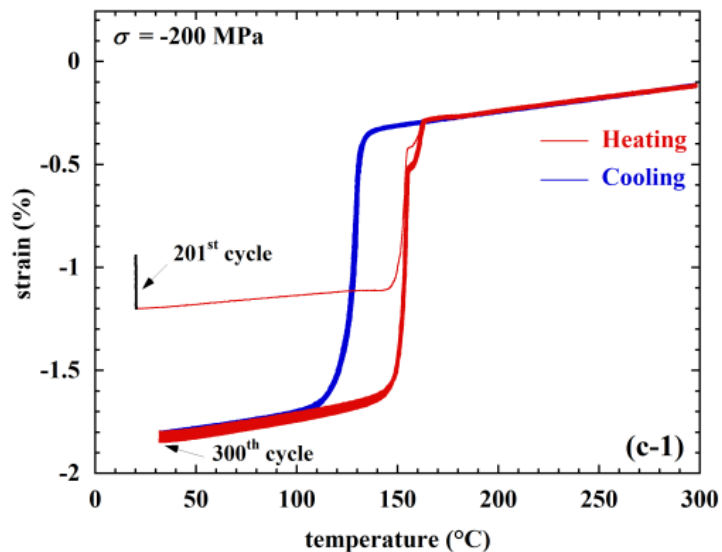
# Development of Shape Memory Alloys:

## How about Durability/Fatigue?



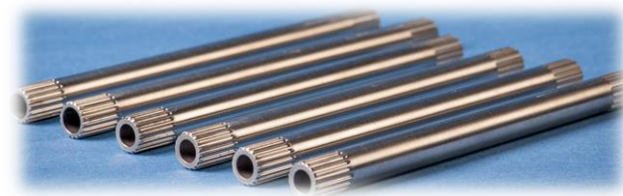
- Loss of actuation strain
- Shifts in transformation characteristics (Hysteresis, temperatures...)

# Durability Assessment Underway...



Data exists up to 1000's of cycles, how about 1M cycles?

Currently collecting durability data on NiTiHf tubes



# Development of Shape Memory Alloys: Challenges and Lessons Learned

## High transformation temperatures

- Above 100 °C
- Good work output
- Thermal stability

## Durability

- Loading history
- Functional fatigue
- Structural fatigue

## Modeling

- Micromechanics
- Phenomenological
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## Workability/Processing

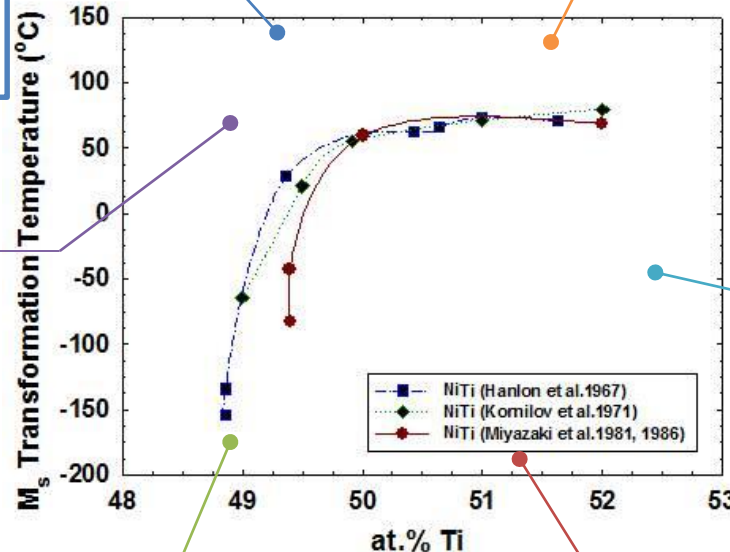
- Ductility
- Composition control
- Heat treatment

## Dimensional stability

- Cyclic stability
- Stress-strain relationship

## Certification

- Testing standards
- Material certification
- Database



# Processing and Workability of HTSMAs

## NiTiPt

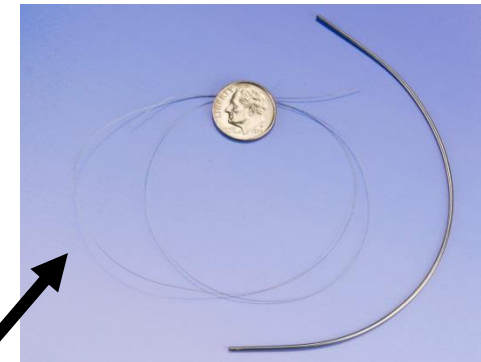
**Induction Melt  
+  
Homogenization**



**Extrusion**

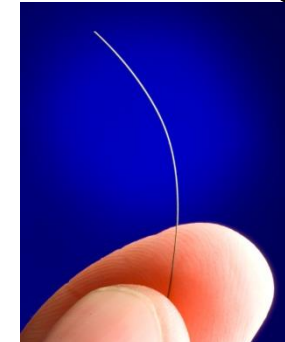


**Wire Grinding**



**44 & 5 mil NiTiPt**

**Wire Drawing**



**5 mil NiTiPt wire**

**Multiple-Pass Extrusion  
60 mil NiTi-20Pt rod**



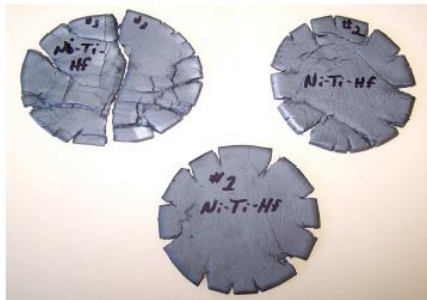


# Processing and Workability of HTSMAs

## NiTiHf



Successful hot rolled button (C. Wojcik 2008)



High temperature extrusion proved to be problematic (C. Wojcik 2008)



Successful hot extrusion (rods and tubes)

# Development of Shape Memory Alloys: Challenges and Lessons Learned

## High transformation temperatures

- Above 100 °C
- Good work output
- Thermal stability

## Durability

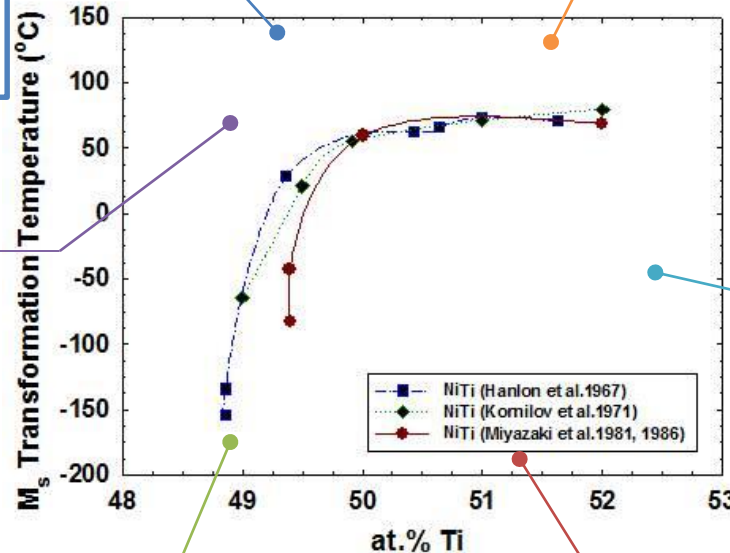
- Loading history
- Functional fatigue
- Structural fatigue

## Modeling

- Micromechanics
- Phenomenological
- Evolutions/transients

## Workability/Processing

- Ductility
- Composition control
- Heat treatment



## Dimensional stability

- Cyclic stability
- Stress-strain relationship

## Certification

- Testing standards
- Material certification
- Database



# Certification and Test Standards

## ASTM Standards for biomedical and or superelastic

- F2004-05
- F2005-05
- F2063-05
- F2082-06
- F2516-07
- F2633-07

## ASTM Standards for SMA Actuation

- **None**



# Certification and Test Standards

## ASTM Standards for biomedical and or superelastic

- F2004-05
- F2005-05
- F2063-05
- F2082-06
- F2516-07
- F2633-07



## ASTM Standards for SMA Actuation

- **None**



**Deliver the first ever regulatory agency-accepted material specification and test standards for shape memory alloys as employed as actuators for commercial and military aviation applications**



# Promoting Growth of SMA Technologies....

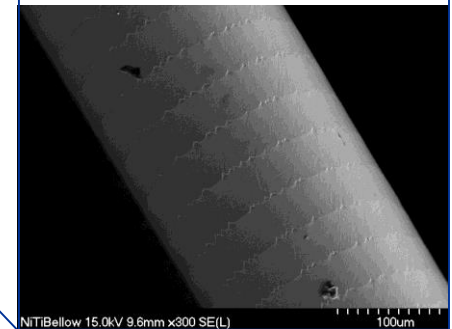
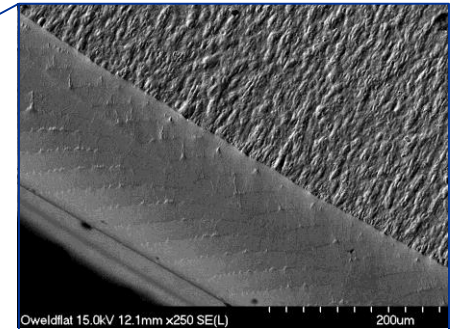
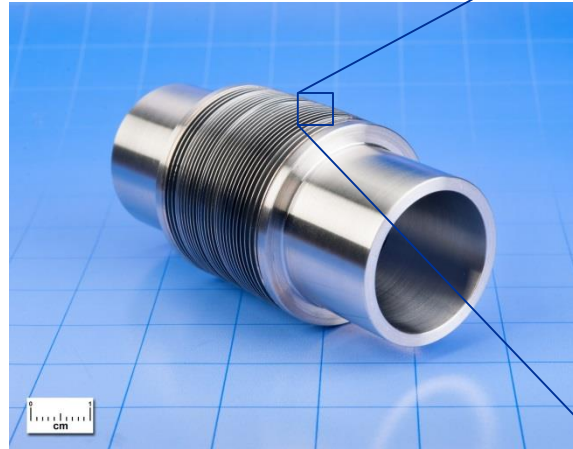
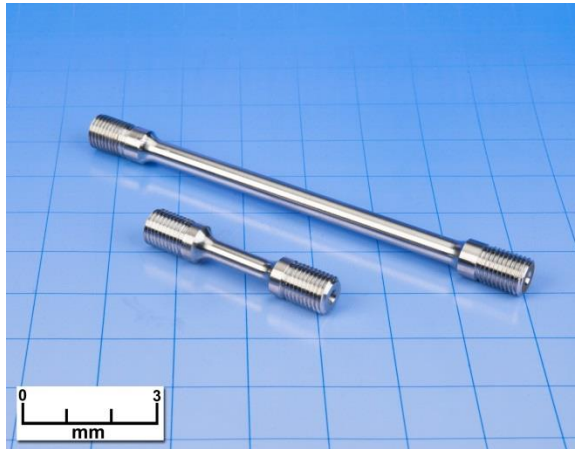




# Applications of SMAs



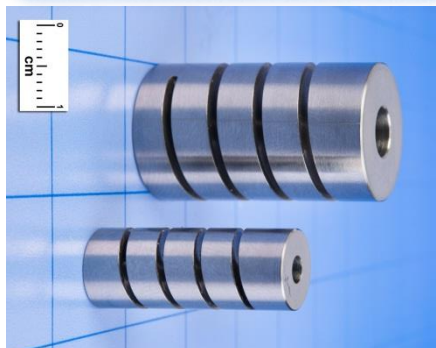
# Some SMA Components



NASA C-2012-1098



National Aeronautics and Space Administration  
John H. Glenn Research Center at Lewis Field





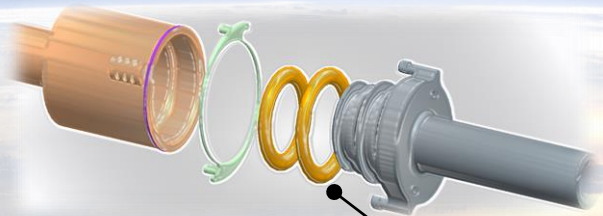
# Shape Memory Alloy Applications

## Space



### SMA Bellows

- Dynamic sealing
- Fluid handling
- Flexibility (structure alignment)



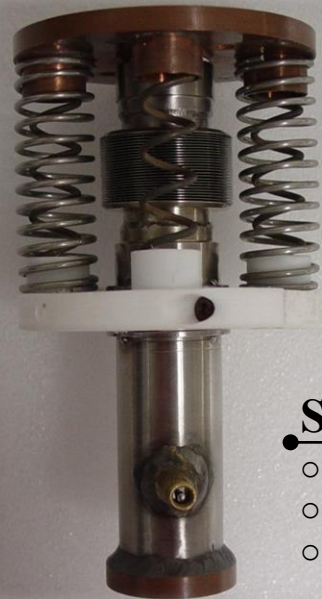
### SMA Docking Coupling

- Cryogenic transfer coupling
- Orbital propellant depots
- Propellant handling/protection



### SMA Spring Tire

- Superelastic technology
- Lunar rovers
- Terrestrial tires



### SMA rock splitters



### SMA Thermal Switch

- Thermal management
- Clean & spark-free operation
- Passive or active control



### SMA Bearings

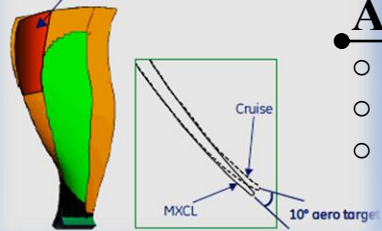
- Corrosion resistant
- Non-galling properties
- High yield

RXN

# Shape Memory Alloy Applications

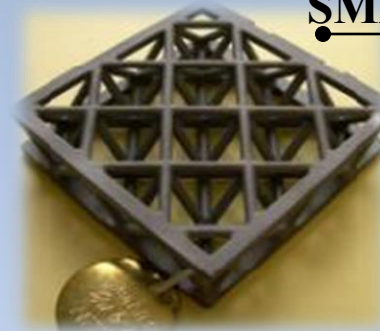
## Aeronautics

Shape change region



### Adaptive Fan Blade

- Embedded SMA actuators
- Aerodynamic efficiency
- Specific fuel consumption reduction

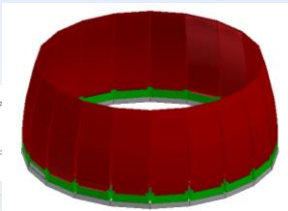
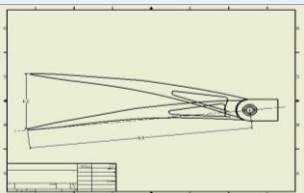


### SMA Cellular Structures

- Airframe and engine components
- Morphing airfoils
- Light weight trusses

### The Mars Atmosphere and Volatile Evolution (MAVEN) mission.

- SMA Pinpullers (From *TiNi Aerospace*) were used to secure and release deployables



### Variable Area Nozzle

- High bypass turbofan
- SMA torque tubes provide flap rotation
- Engine noise reduction





*Thank You*

